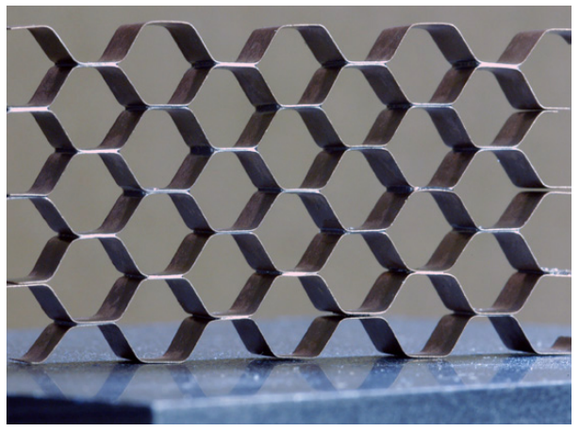
# Cellular Shape Memory Alloy Structures: Experiments & Modeling



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# Report Documentation Page

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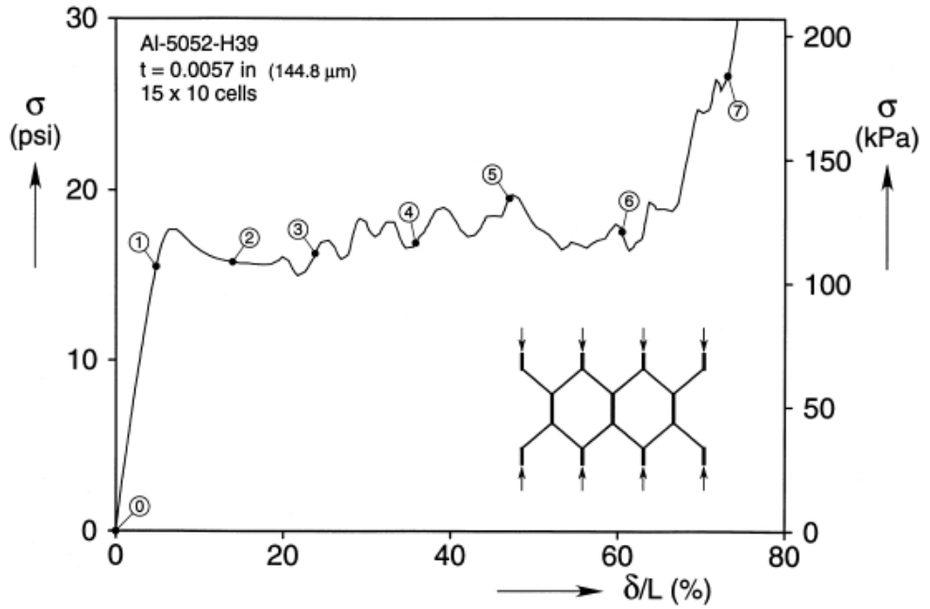
# Outline

- Background
- Honeycomb specimen fabrication
- Honeycomb characterization
- SMA bending

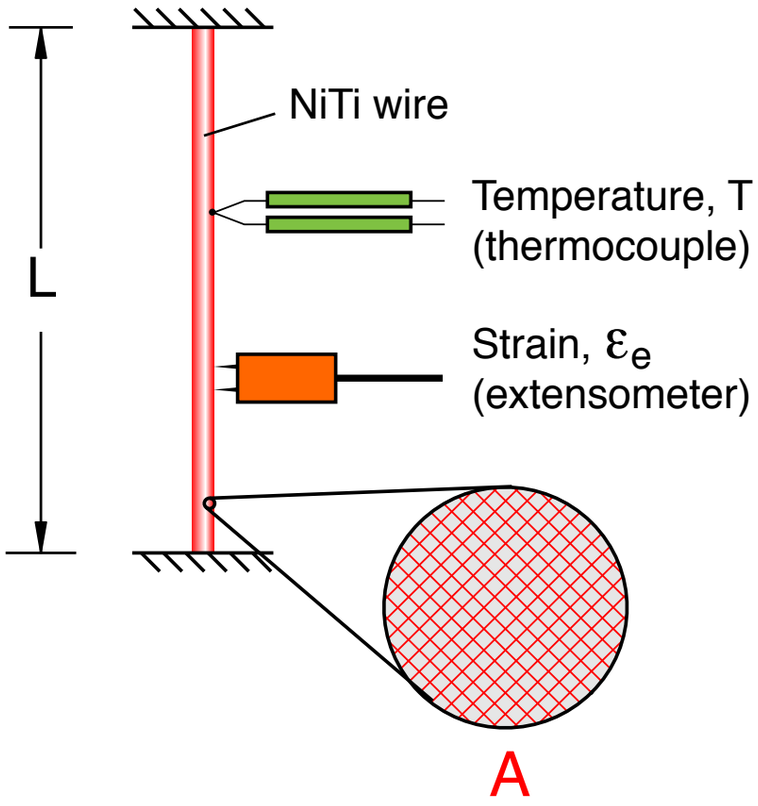
# Background

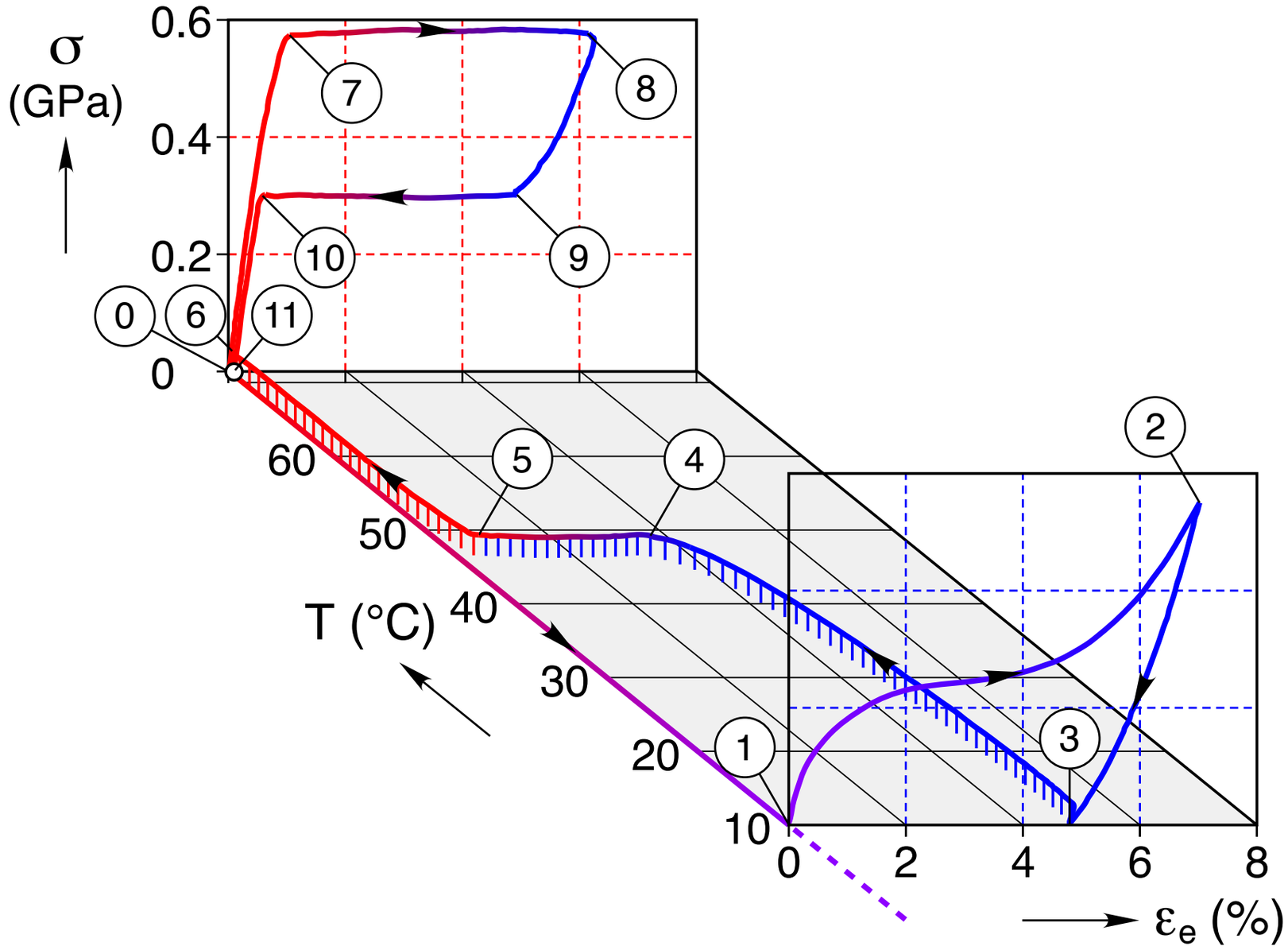
# Compression of Al honeycomb




[Papka/Kyriakides, 1998]

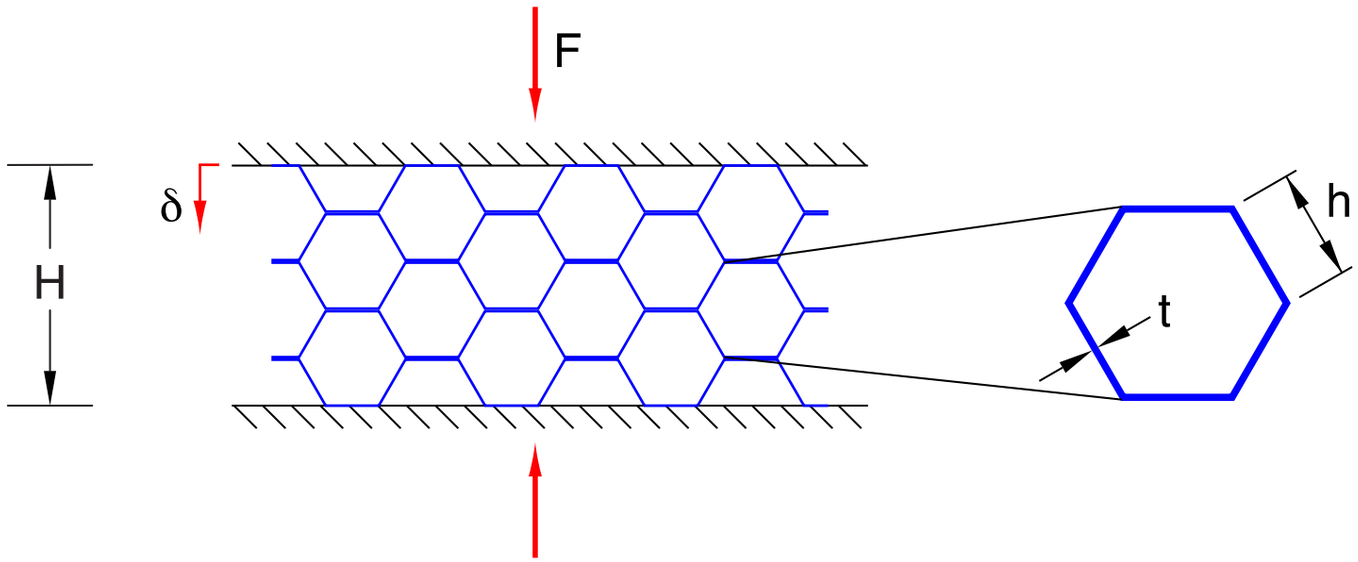
# Nitinol (SM) wire: shape memory & superelasticity




Shape memory & superelasticity

# Thin-walled honeycomb: scaling laws




relative density $\dfrac{\rho^*}{\rho_s} \propto \dfrac{t}{h}$

global/local bending strain $\dfrac{|\varepsilon^*_{\text{dense}}|}{\varepsilon_{s,\max}} \propto \dfrac{t}{h}$

global/local plateau stress $\dfrac{|\sigma^*_0|}{\sigma_{s,0}} \propto \left(\dfrac{t}{h}\right)^2$

global/local modulus $\dfrac{E^*}{E_s} \propto \left(\dfrac{t}{h}\right)^3$

[Gibson/Ashby, 1997]

Comparison of Aluminum & NiTi honeycomb for same recoverable global strain

| Property | Al | NiTi | NiTi/Al |
|---|---|---|---|
| $\varepsilon^*_{\text{dense}}$ | -50% | -50% | 1 |
| $\varepsilon_{s,\max}$ | 0.5% | 5% | 10 |
| $t/h$ | $10^{-2}$ | $10^{-1}$ | 10 |
| $\lvert\sigma^*_0\rvert/\sigma_{s,0}$ | $10^{-4}$ | $10^{-2}$ | 100 |
| $E^*/E_s$ | $10^{-6}$ | $10^{-3}$ | 1000 |

# Advantages of SMA honeycombs

Combine benefits of light-weight cellular structures
with Shape Memory Alloy (SMA) adaptive behavior

## Metallic honeycombs

- Low density
- High specific stiffness
- Large specific energy absorption

## NiTi SMA

- Shape memory effect & superelasticity
- High strength, ductility,
- Corrosion resistance, biocompatibility

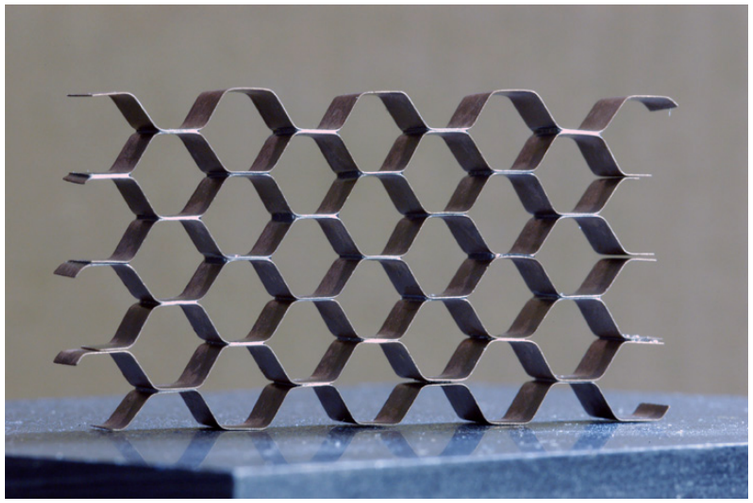
Combination

- Amplified strain recovery

  5% ➡ 50%

- Reduced thermal lag

  $\tau$ ➡ $\tau$ /10



NiTi hexagonal honeycomb
(5.7% dense, 0.37 g/cc)

# Potential applications of NiTi Cellular Structures

## Overload protection

- Amplified superelasticity, reusable energy absorber
- Lightweight, resilient, damage tolerant

## Vibration isolation

- Adaptive damping

## Thermal actuators & adaptive structures

- Improved response time, amplified stroke

## Thermal & acoustic management

- Adaptive thermal conductivity & acoustic impedance

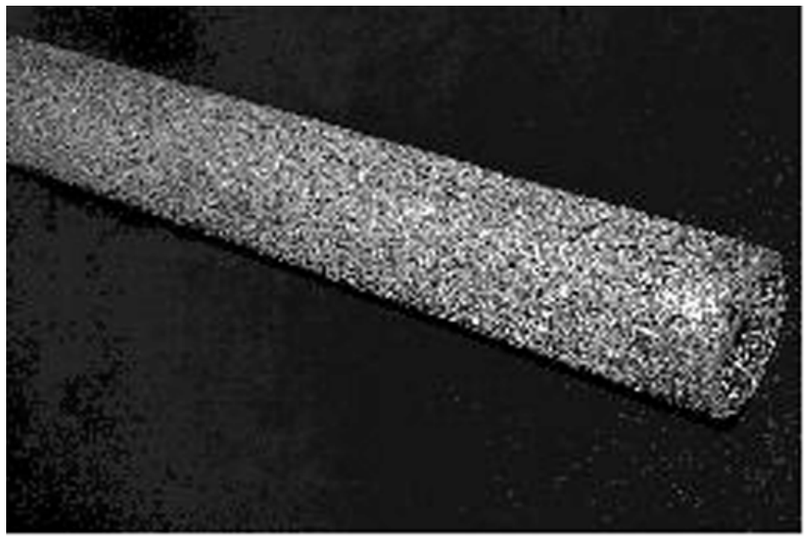
## Biomedical implants & devices

- Lightweight, sparse, tailorable properties, deployable

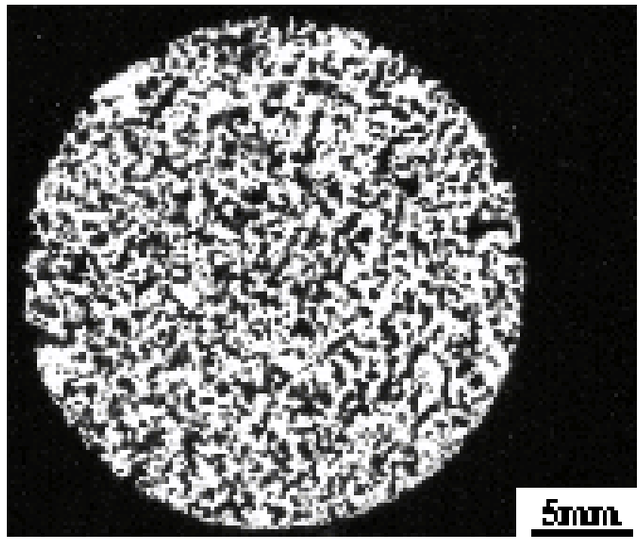
# Fabrication & Metallurgy

# Prior Attempts: Powder Metallurgy

Porous SMAs

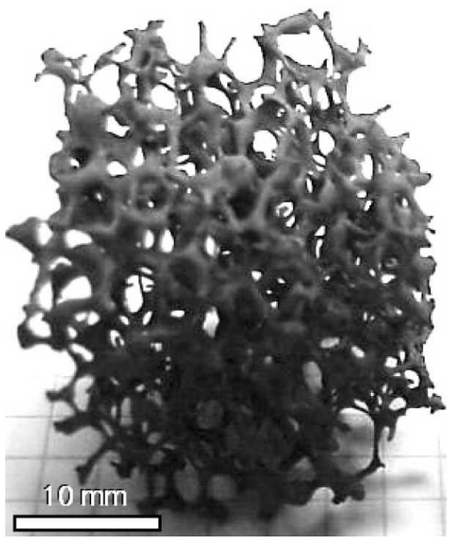


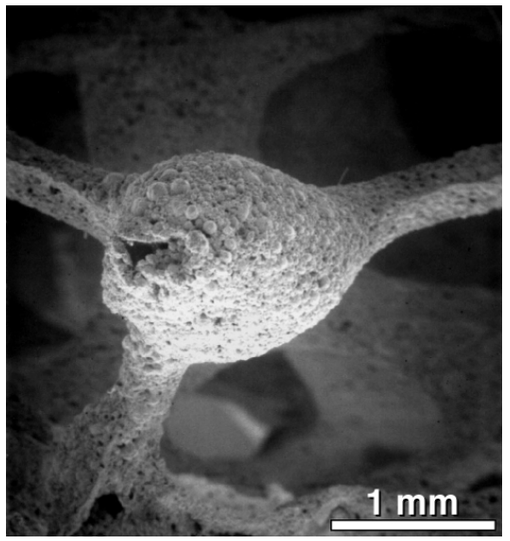
50% dense NiTi bar
hot isostatic pressing of elemental powders
[Naval Research Lab, V. DeGiorgi]




40% dense NiTi bar
combustion synthesis
[Li Rong, China]

SMA foam




5% dense NiTi open-cell foam
Powder process with sacrificial precursor
[Grummon/Shaw, 2002]

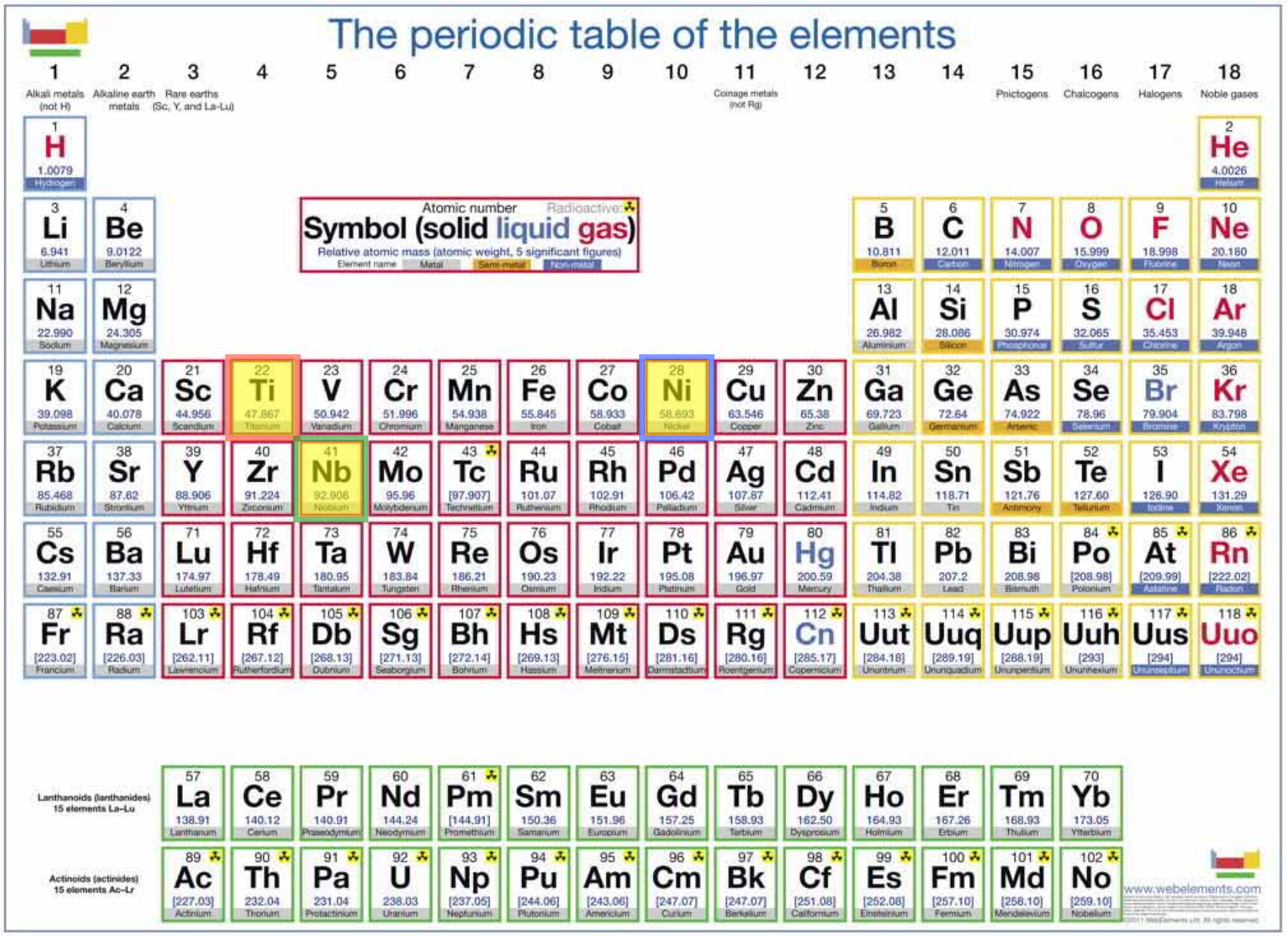
# Technological Barrier Overcome

## Long-standing difficulty:

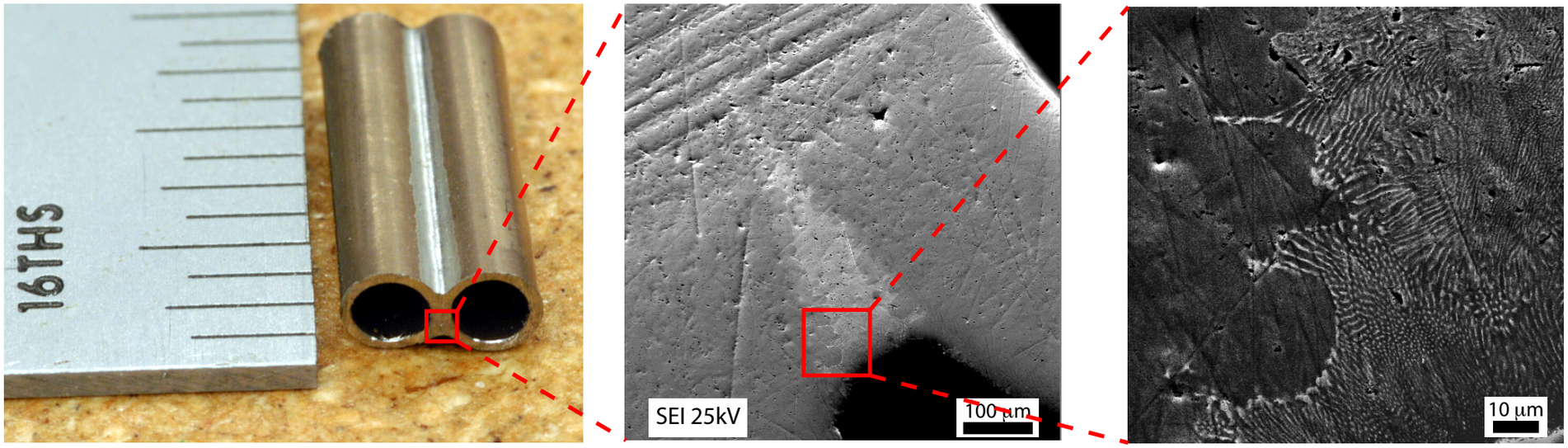
- Joining NiTi to itself or anything else
- Usually requires mechanical attachment/crimping
- Gluing is a very low strength option

## Metallurgical bonds:

- Sensitive to interstitial contaminants (C, O, N).
- Laser welding in inert gas
  - Tricky (& proprietary), but some recent success.
  - Requires line-of-sight access.
- Soldering
  - Requires very aggressive fluxes to remove Ti-oxides.
  - Low strength
- Nb-reactive bonding (our process)
  - Discovered in 2004
  - Self-fluxing
  - Strong, ductile joints
  - Vanadium also works well

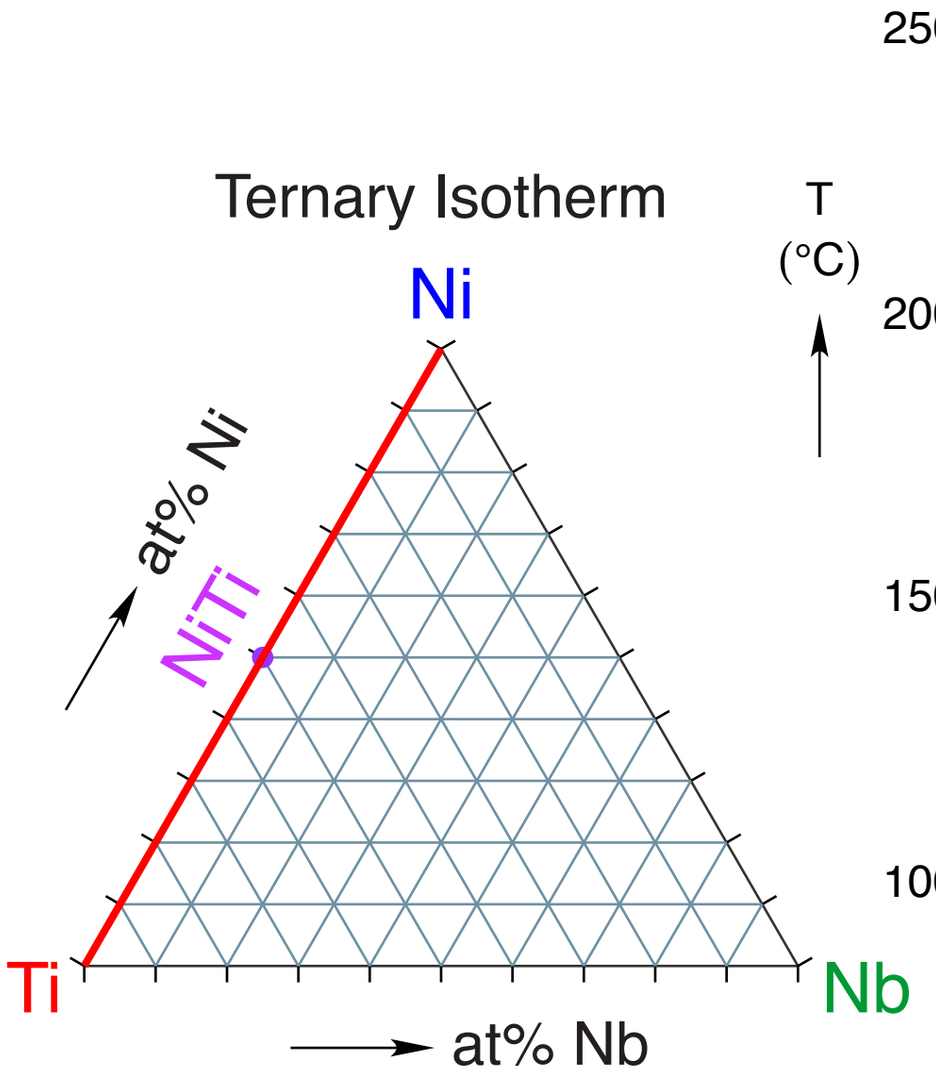

The periodic table of the elements
1 Alkali metals (not H)
2 Alkaline earth metals
3 Rare earths (Sc, Y, and La-Lu)
4 5 6 7 8 9 10
11 Coinage metals (not Rg)
12 13 14
15 Pnictogens
16 Chalcogens
17 Halogens
18 Noble gases
Atomic number
Radioactive:
Symbol (solid liquid gas)
Relative atomic mass (atomic weight, 5 significant figures)
Element name
Metal
Semi-metal
Non-metal
Lanthanoids (lanthanides) 15 elements La–Lu
Actinoids (actinides) 15 elements Ac–Lr
www.webelements.com

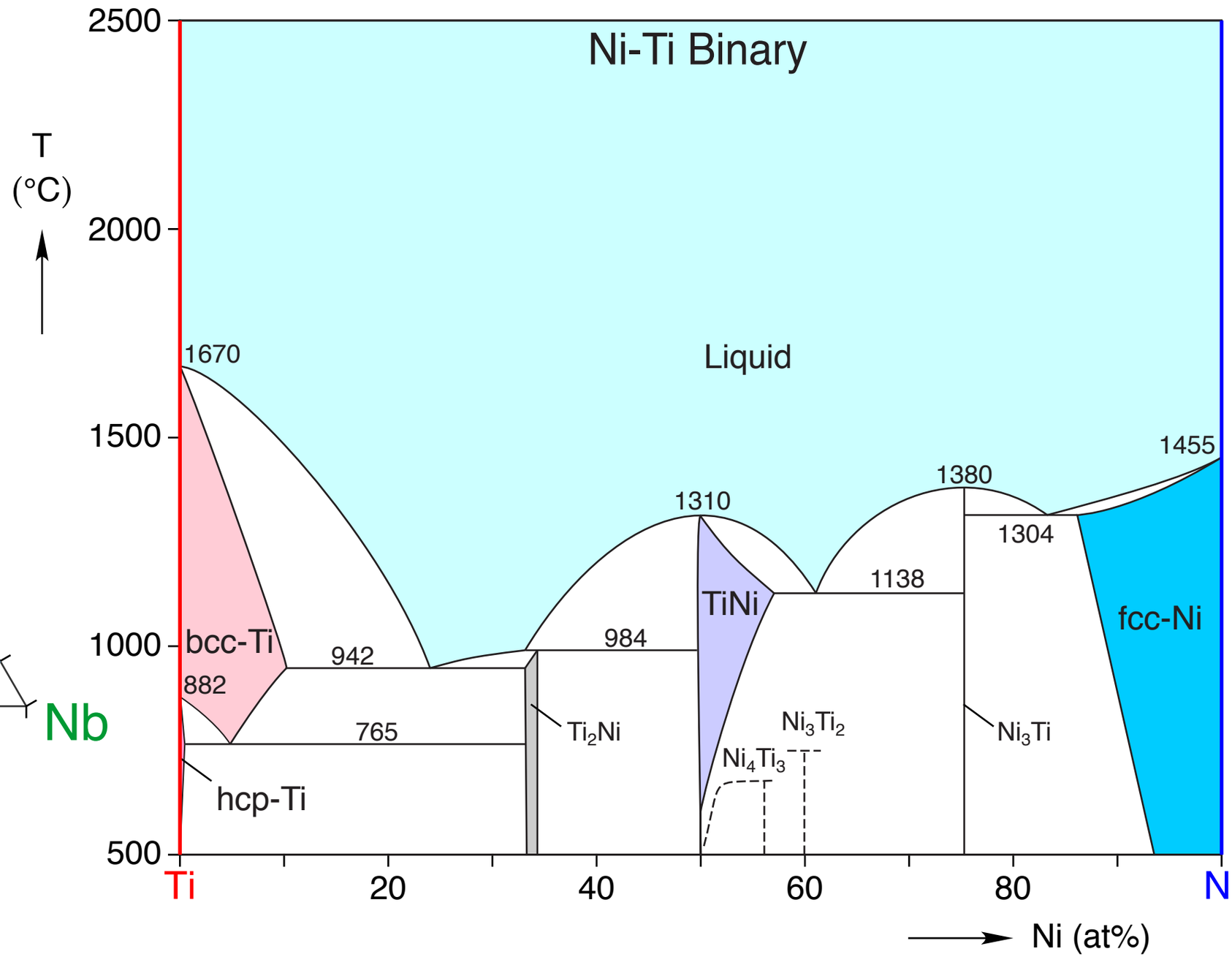
# Discovery of a Nb-based braze for joining wrought NiTi

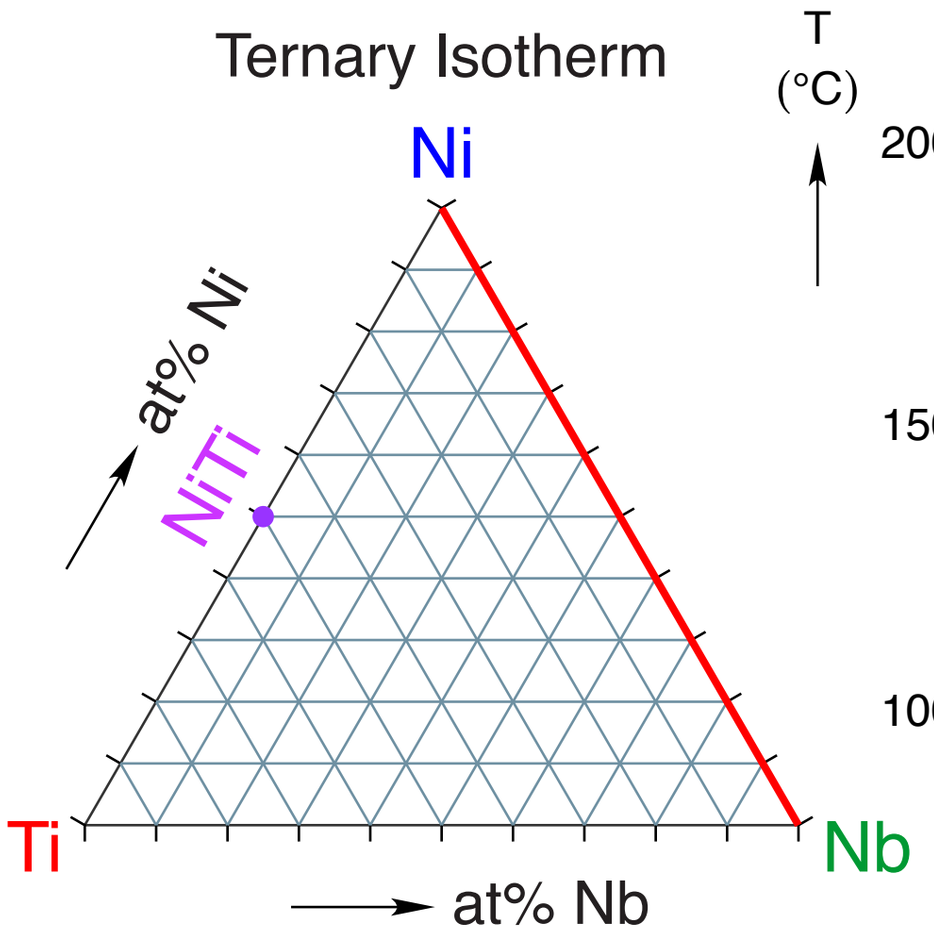


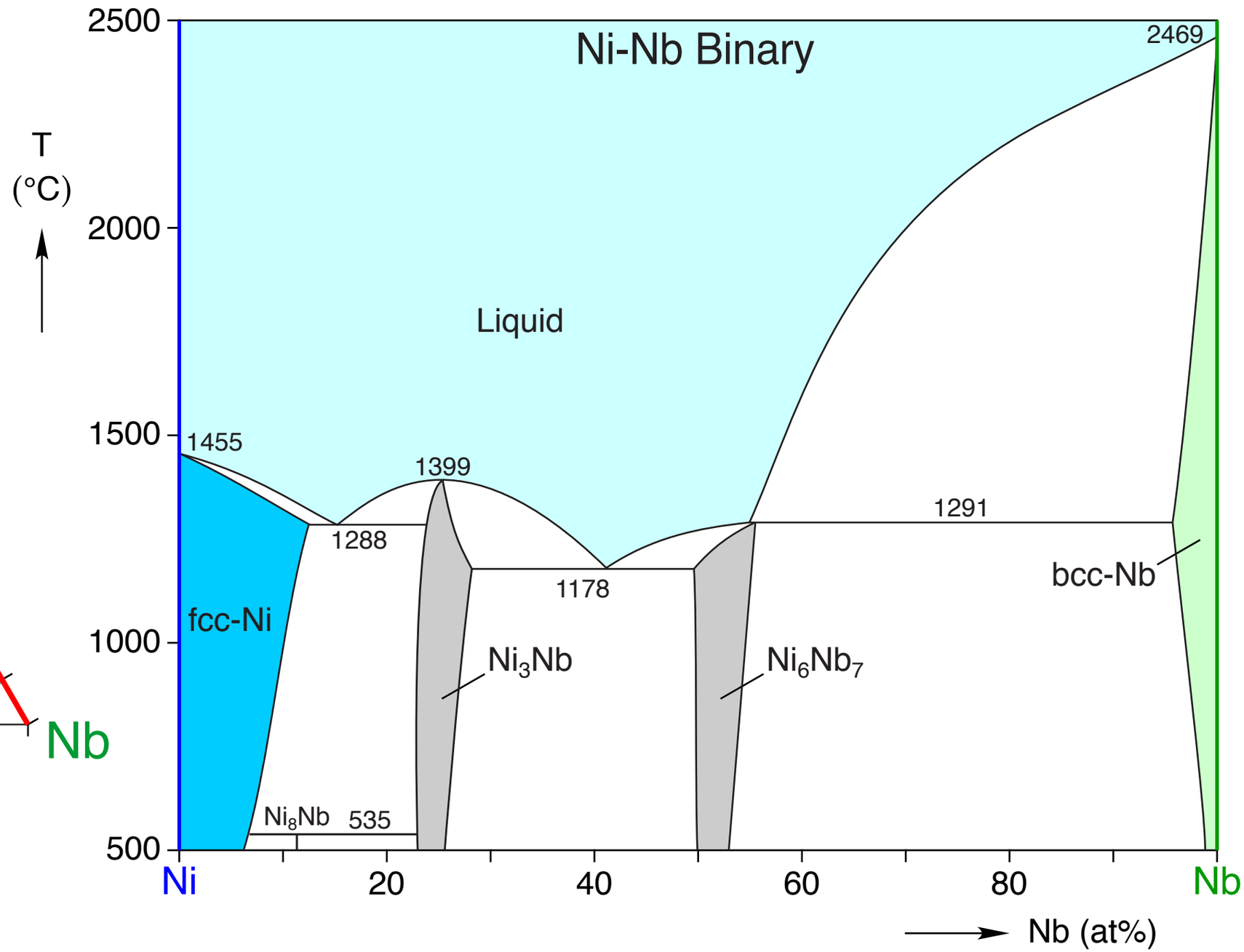

[Shaw/Grummon (UM/MSU) U.S. patent 7,896,222, issued March 1, 2011]

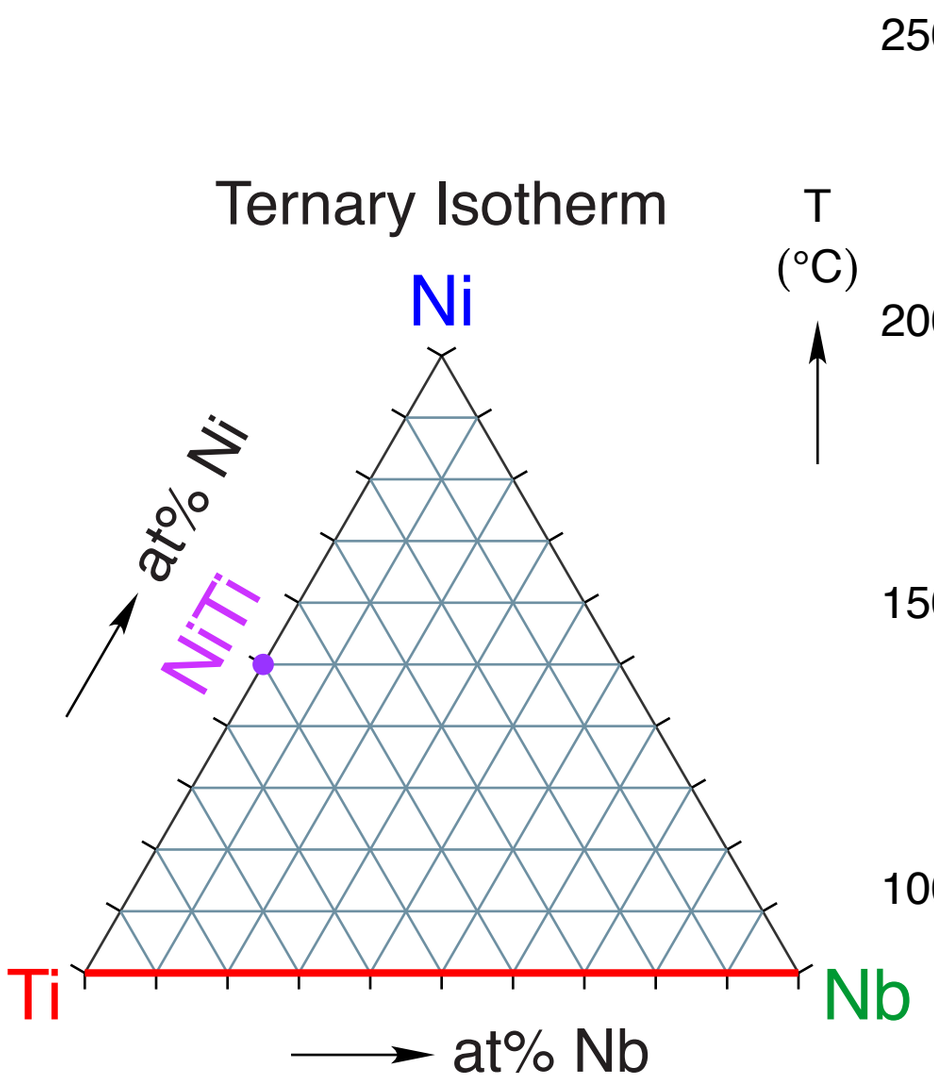
60 NiTi-tube array (32 % dense)

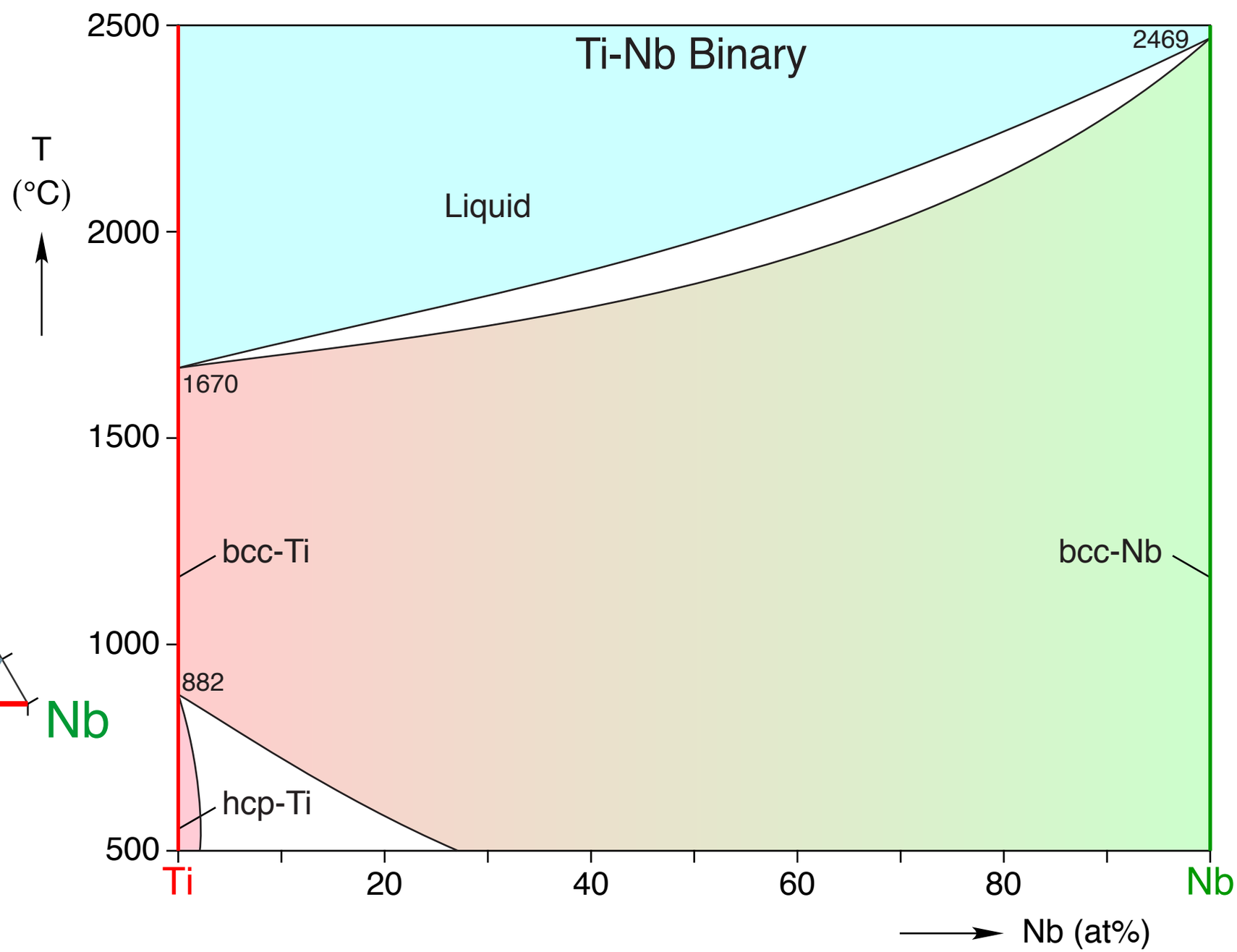

Ternary Isotherm
Ni
at% Ni
NiTi
Ti
Nb
at% Nb

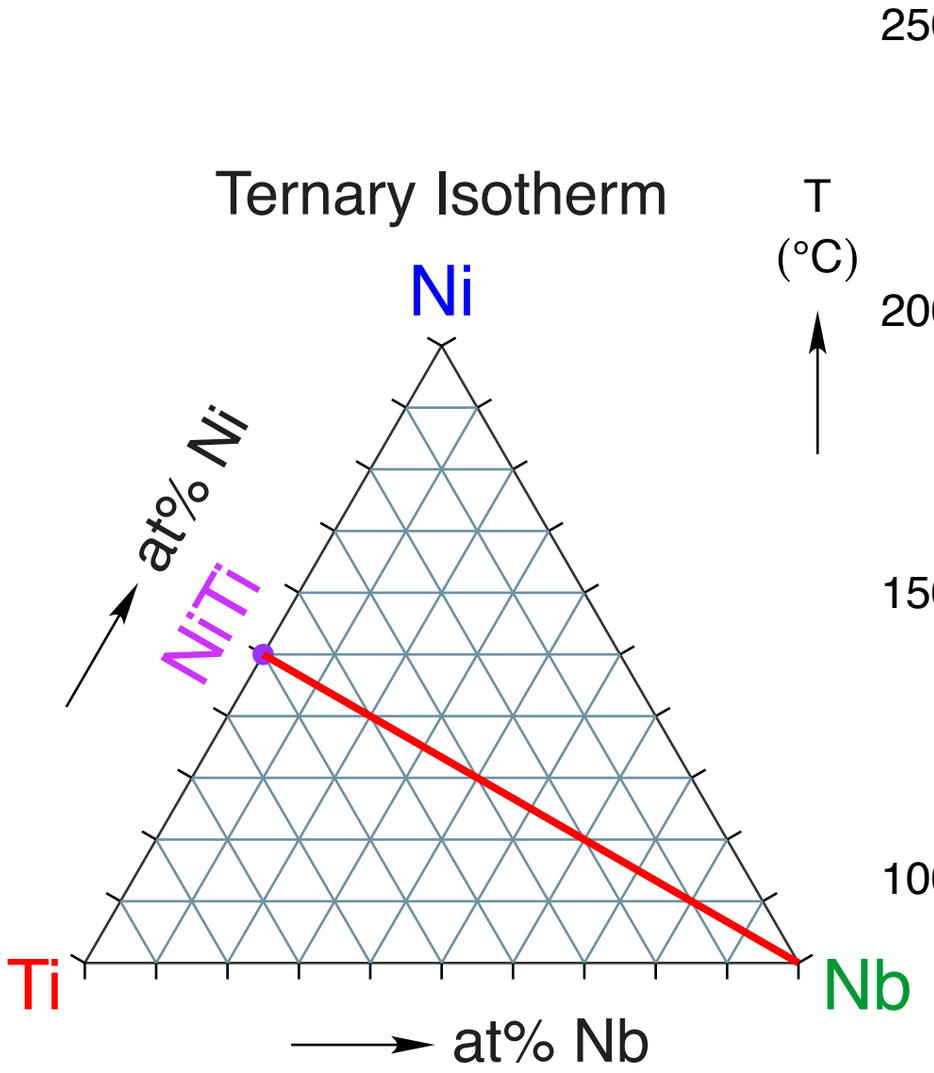

Ni-Ti Binary
T
(°C)
2500
2000
1500
1000
500
Liquid
1670
1455
1380
1310
1304
1138
984
942
882
765
bcc-Ti
hcp-Ti
TiNi
fcc-Ni
Ti2Ni
Ni3Ti2
Ni4Ti3
Ni3Ti
Ti
20
40
60
80
Ni
Ni (at%)

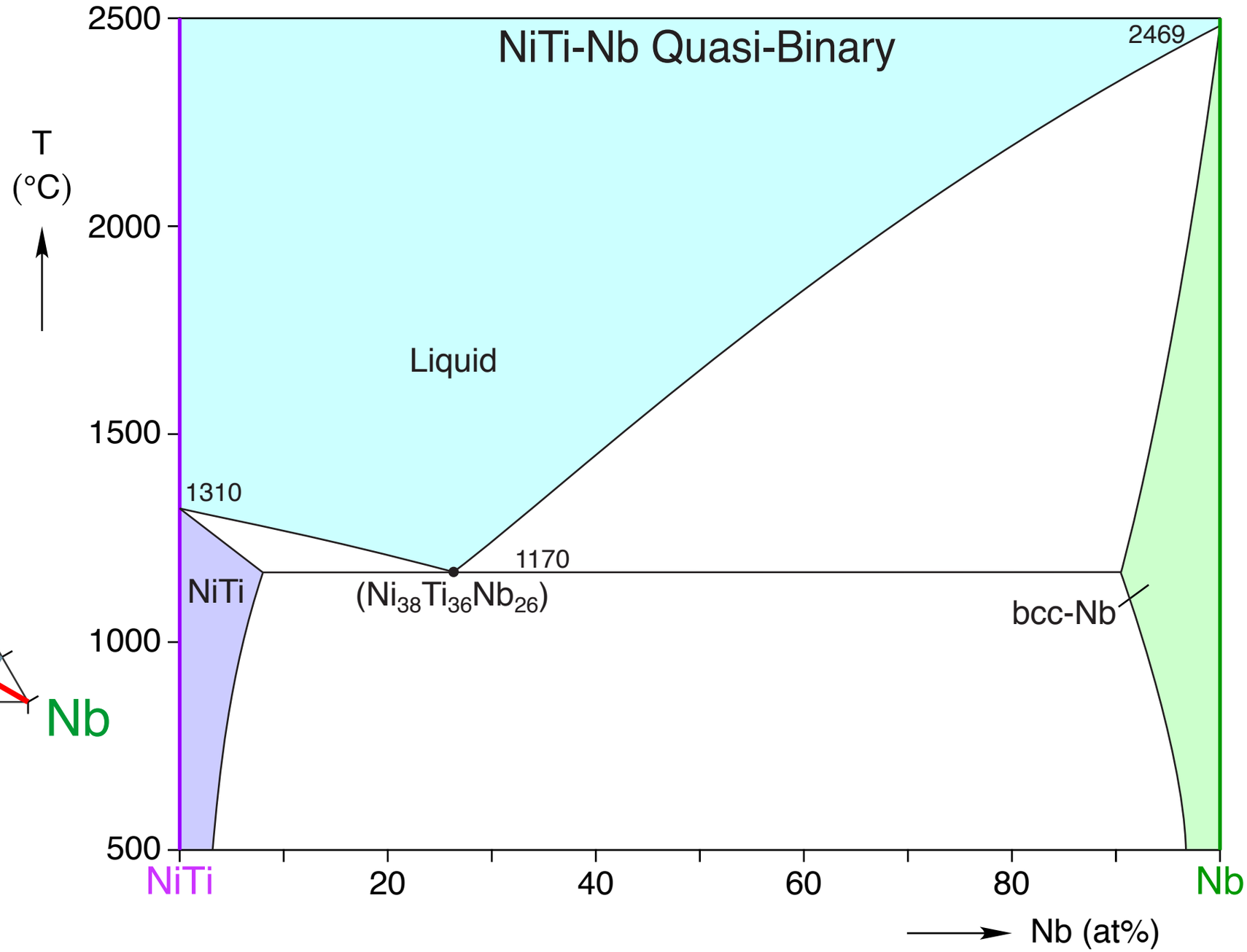

Ternary Isotherm
Ni
at% Ni
NiTi
Ti
Nb
at% Nb


Ni-Nb Binary
T
(°C)
2500
2000
1500
1000
500
Liquid
2469
1455
1399
1288
1291
1178
bcc-Nb
fcc-Ni
Ni3Nb
Ni6Nb7
Ni8Nb
535
Ni
20
40
60
80
Nb
Nb (at%)

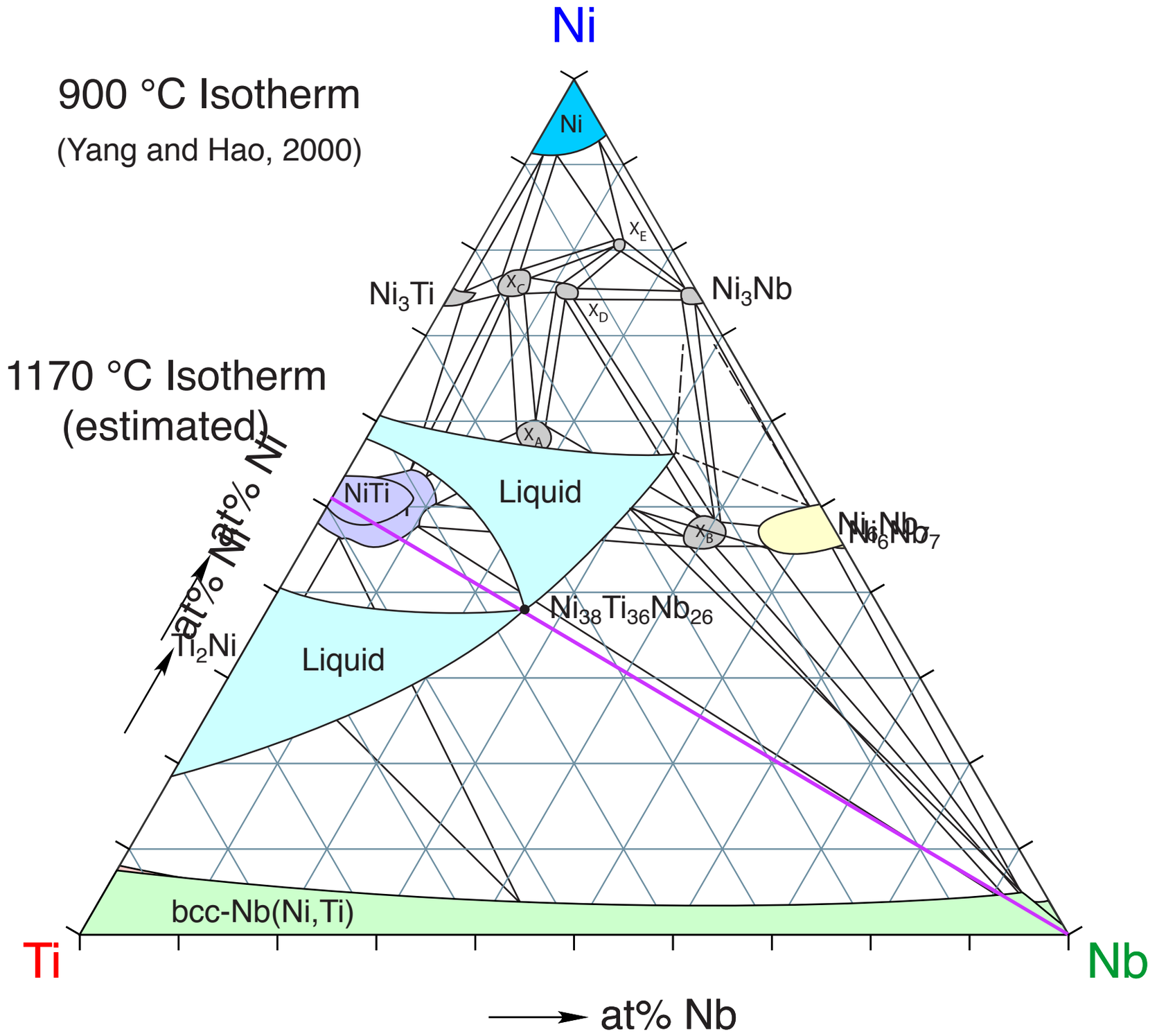

Ternary Isotherm
Ni
at% Ni
NiTi
Ti
Nb
at% Nb


Ti-Nb Binary
T
(°C)
2500
2000
1500
1000
500
Liquid
2469
1670
bcc-Ti
bcc-Nb
882
hcp-Ti
Ti
20
40
60
80
Nb
Nb (at%)

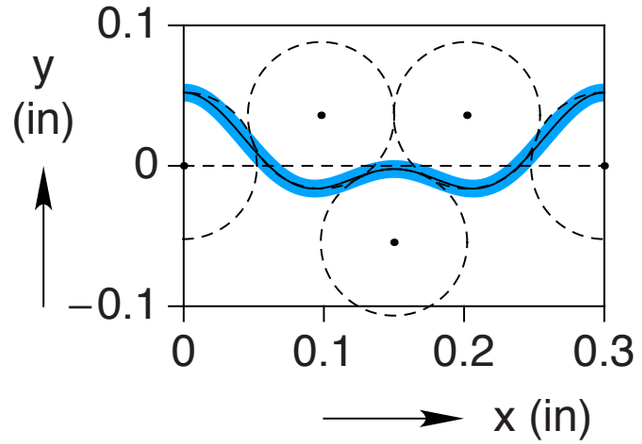

Ternary Isotherm
Ni
at% Ni
NiTi
Ti
Nb
at% Nb


T
(°C)
2500
2000
1500
1000
500
NiTi-Nb Quasi-Binary
2469
Liquid
1310
1170
NiTi
(Ni38Ti36Nb26)
bcc-Nb
NiTi
20
40
60
80
Nb
Nb (at%)

# Quasi-binary Eutectic



# Fabrication Procedure

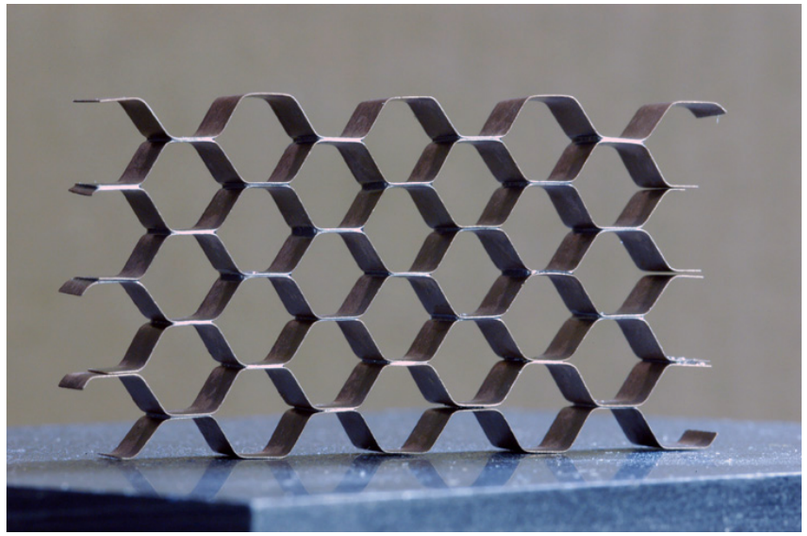


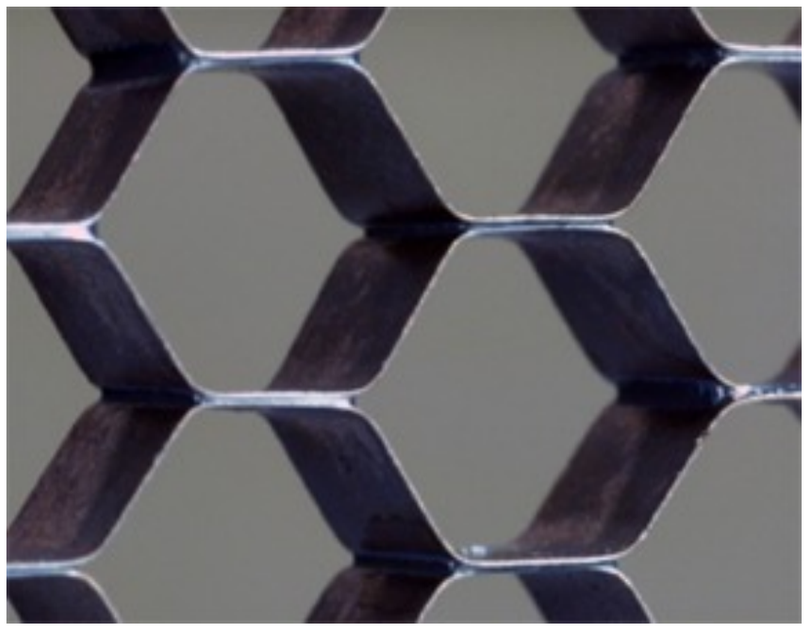

Shape-set of corrugated strips (500 °C)

1. Corrugate SMA strips at 500 °C by shape set die
2. Lay up corrugation layers & Nb foils
3. Vacuum furnace at 1170 °C, 5 min
4. Age at 500 °C, 10 min

# Low-density NiTi cellular specimens

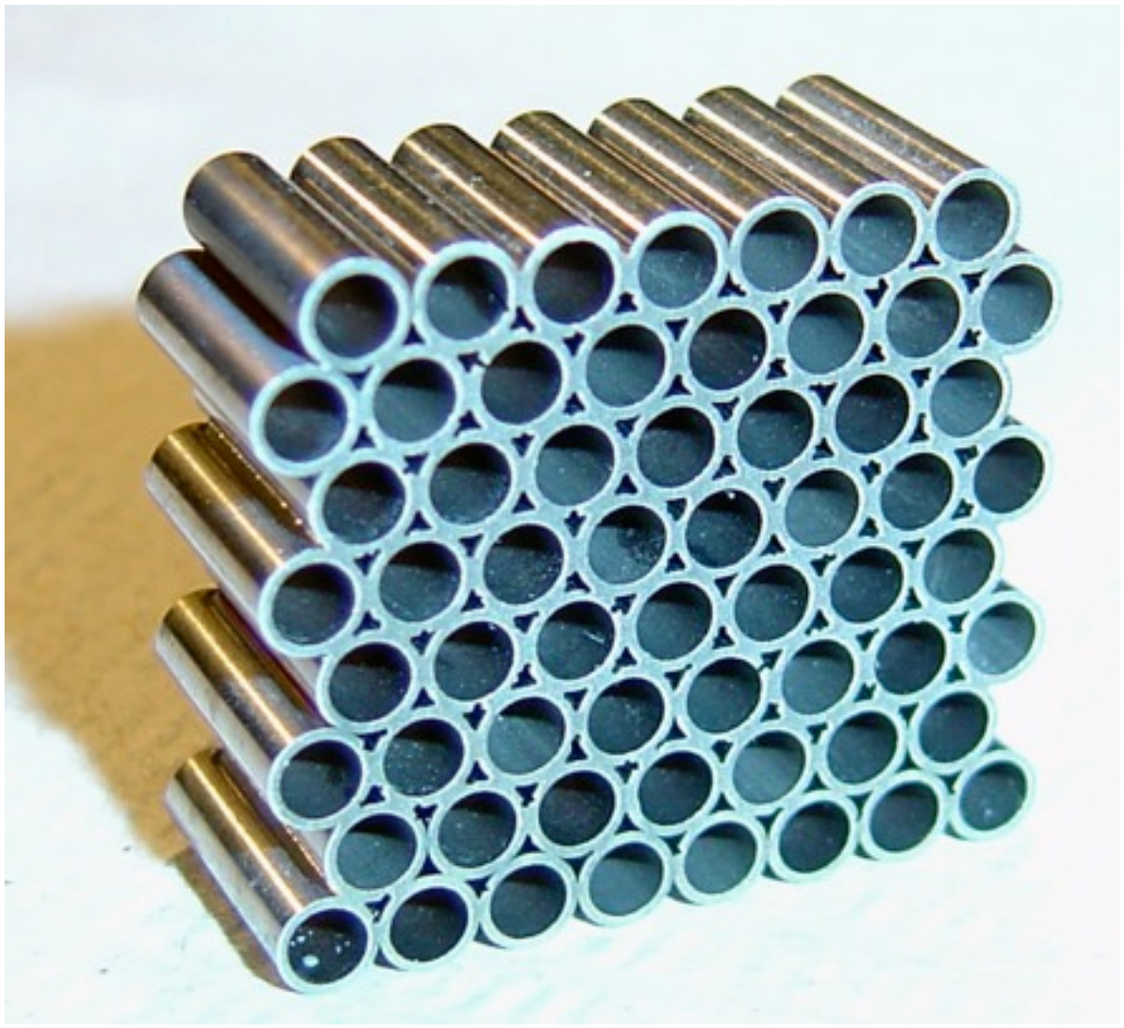
NiTi wavy corrugations

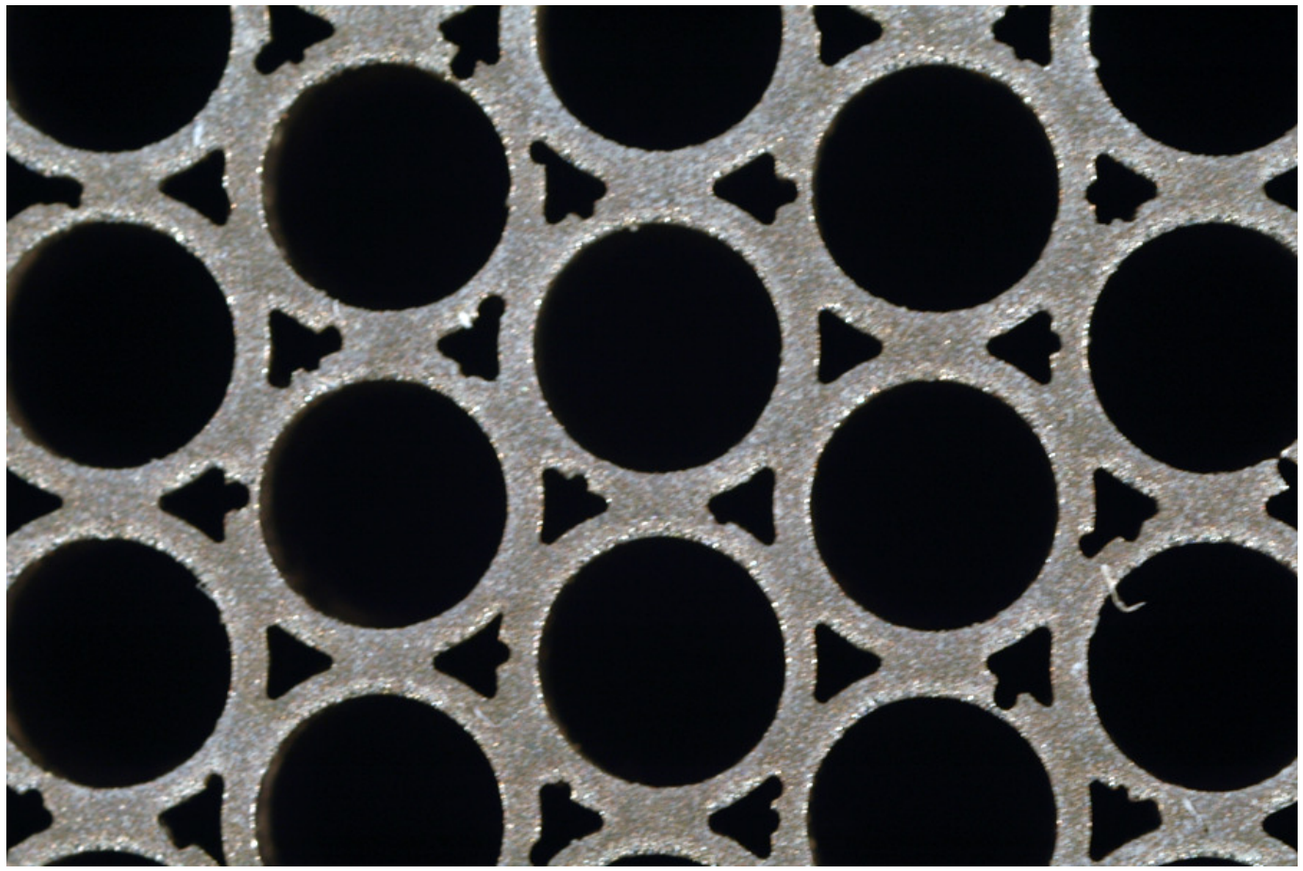




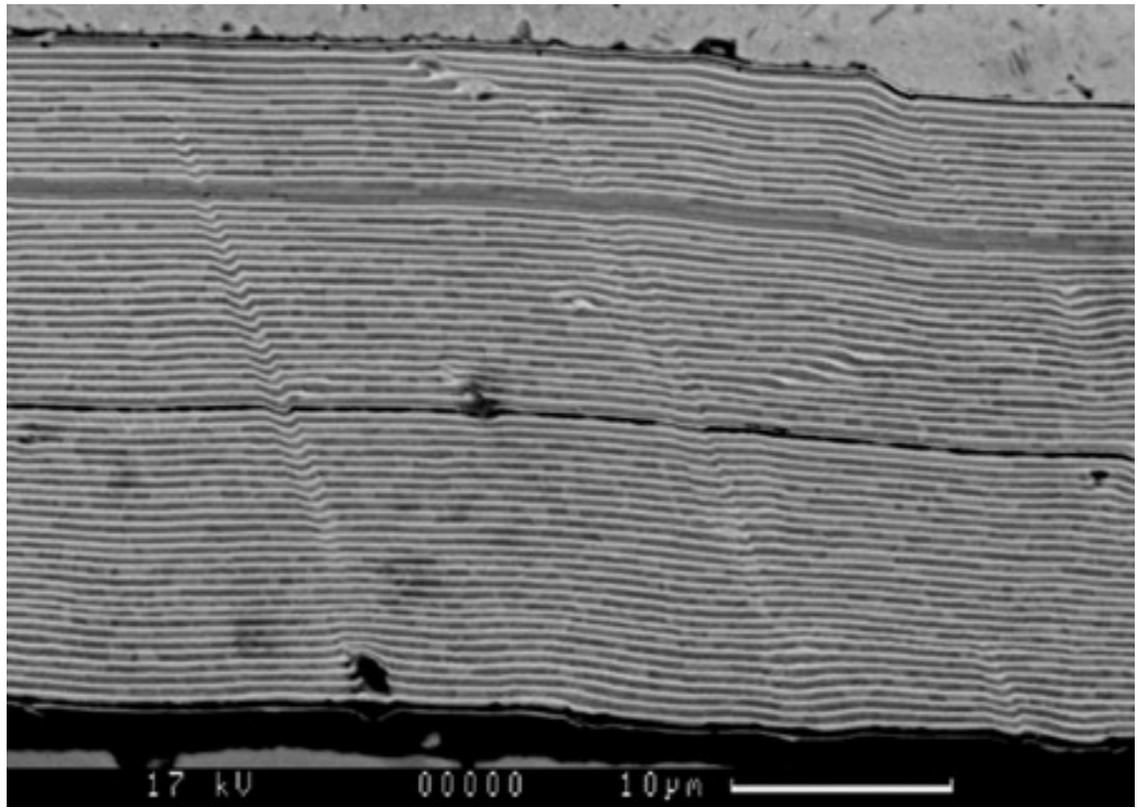
NiTi hexagonal honeycomb
(5.7% dense, 0.37 g/cc)

# Aggressive Reaction

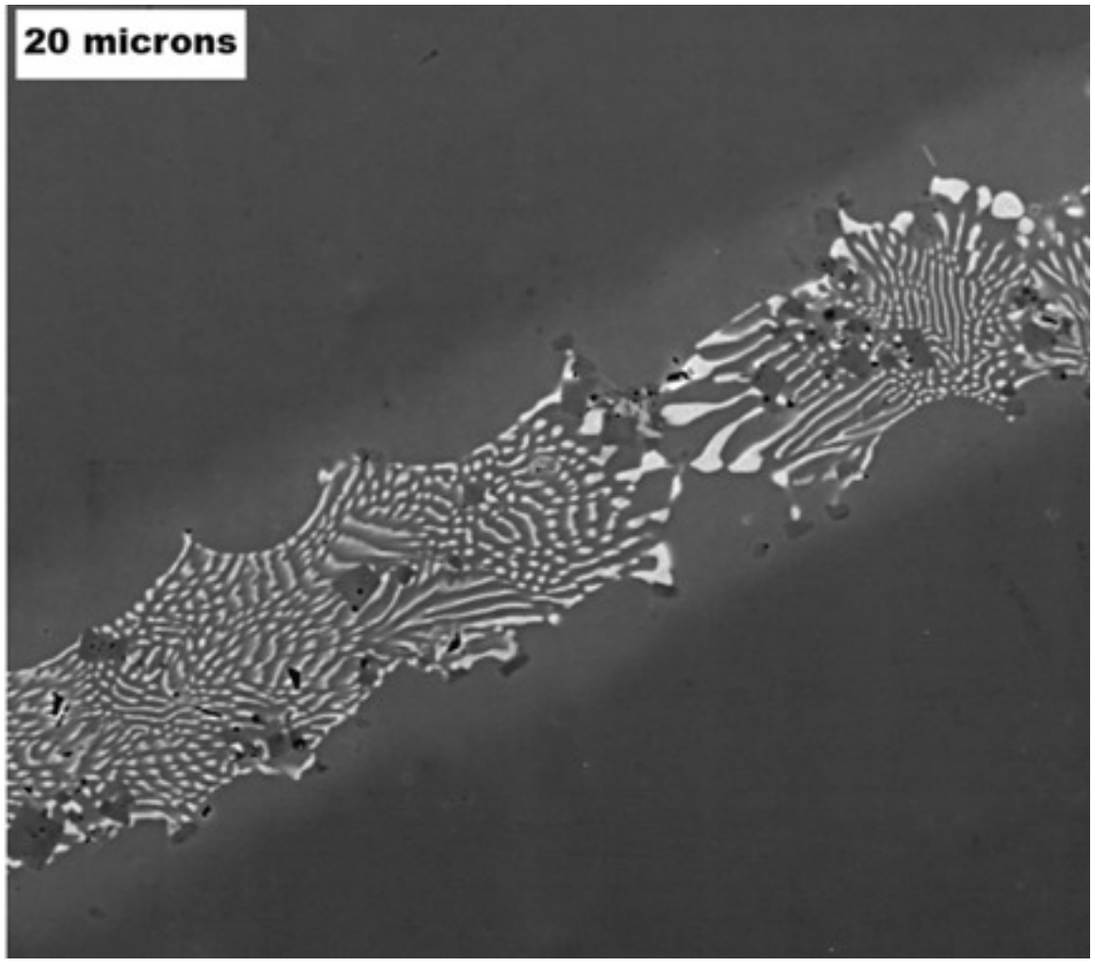




# Advanced Braze Process Development

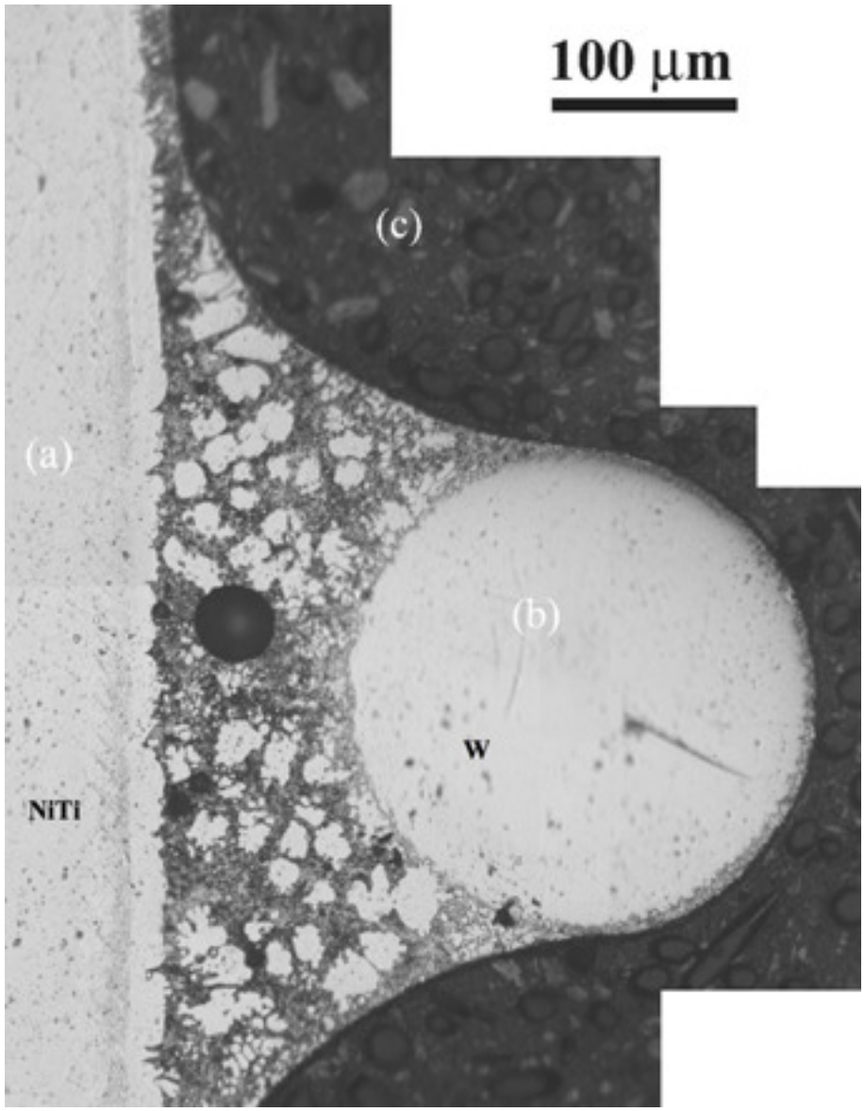



NiTi-Nb multilayer braze foil cross-section
(127 layers, 34 micron thickness total)

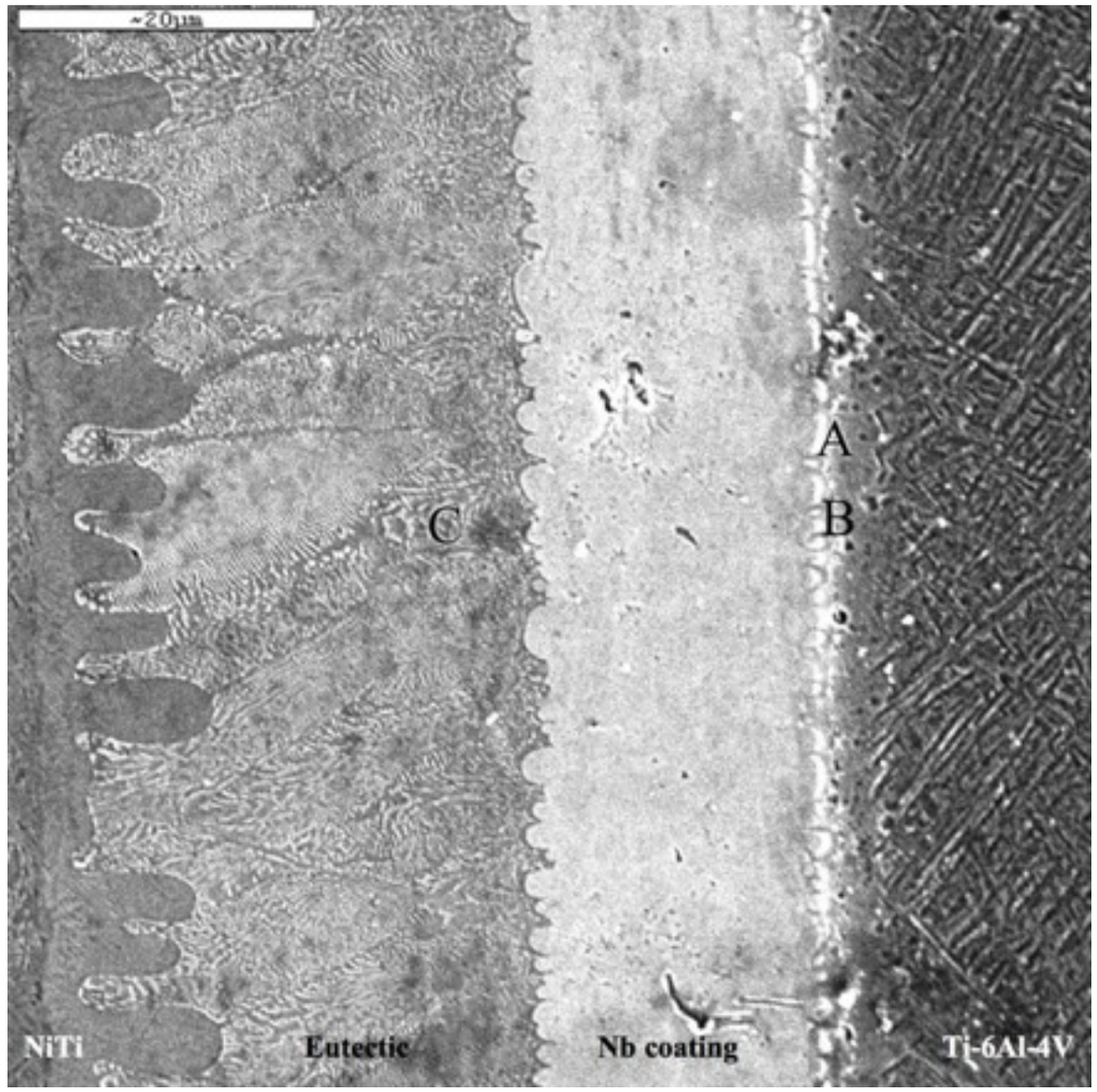



Braze microstructure using
multilayer foil

# Other Heterobonds with NiTi

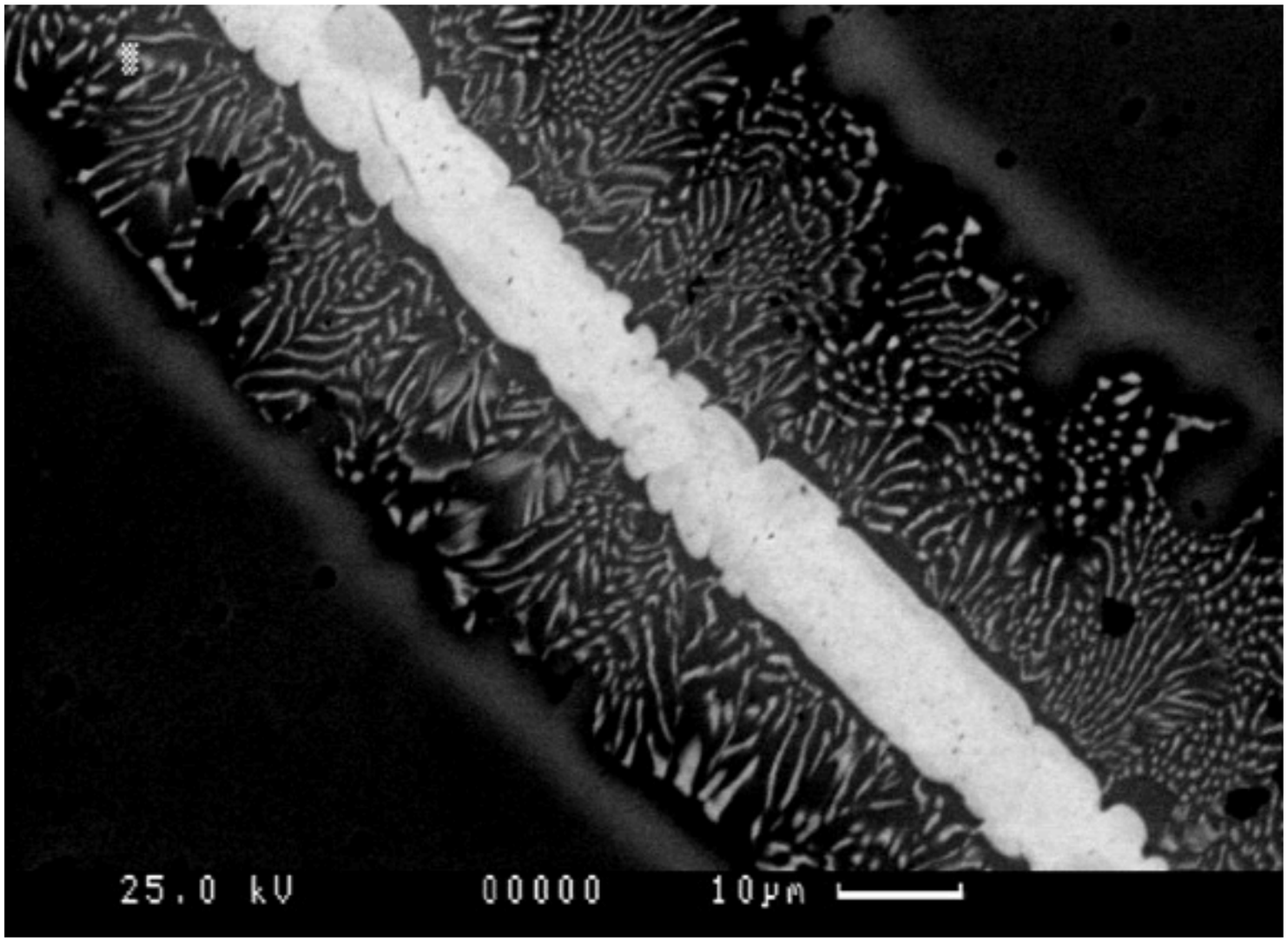



Pure tungsten (W) wire bonded to NiTi alloy




Sputtered Nb  layer bonded between NiTi and Ti-6Al-4V

# Possible Braze for High-temperature SMAs




Braze Joint between two wrought pieces of a $Ni_{24.5}Pd_{25}Ti_{50.5}$ HTSMA
(HTSMA from R. Noebe's group, NASA Glenn Research Center)

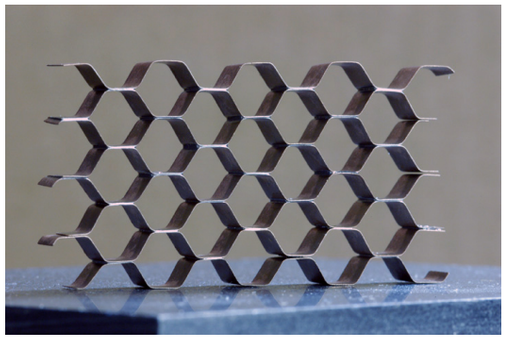
# Fabrication of SMA cellular structures

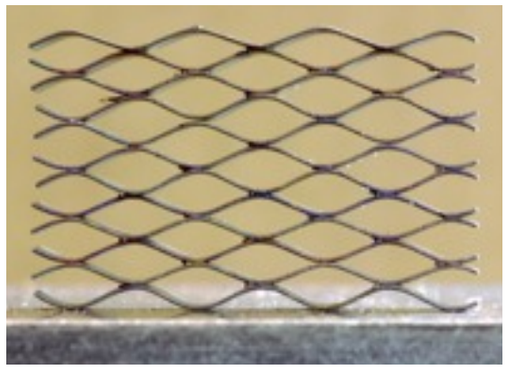
## APPROACH:

- Built-up, low density SMA corrugated structures
- Commercially-available wrought NiTi materials
- Nb-based brazing process

## ACCOMPLISHMENTS:

- Fabricated NiTi SMA specimens:
  - hexagonal honeycombs (~ 5% dense)
  - wavy corrugations (~ 5% dense)
  - close-packed tube array (~ 32 % dense)
- Demonstrated robust braze joints:
  - Up to ~800 MPa tensile strength (butt-joints)
- Preserved adaptive properties of NiTi base material
- Improved layup with self-indexing geometry
- Multi-layer foils improve control of braze stoichiometry
- Positive indications that braze process can be used to join other metal alloys and high-temperature SMAs





# Possible topologies & geometries

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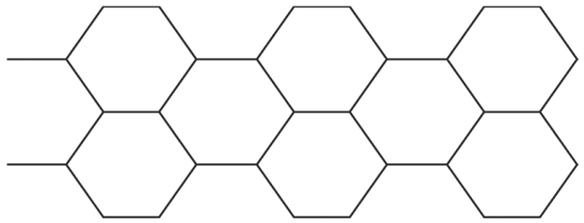

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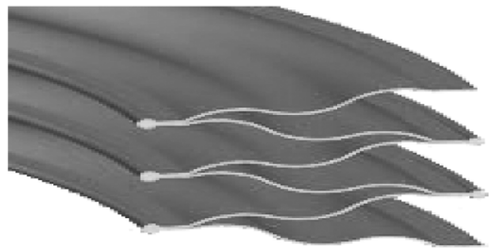

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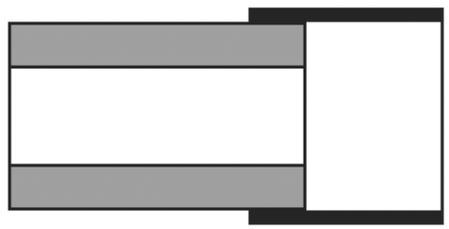

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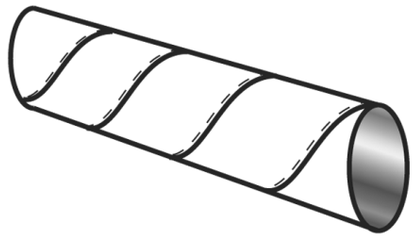

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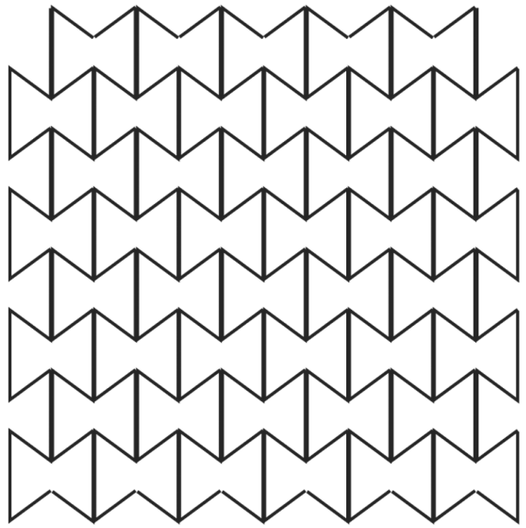

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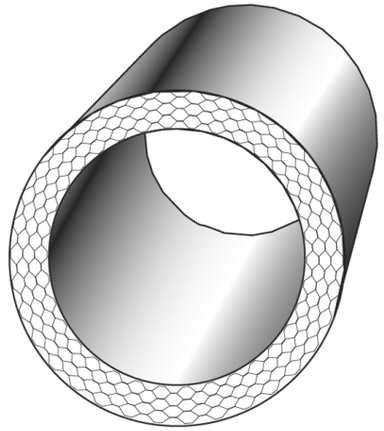

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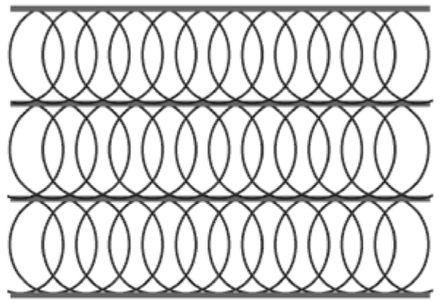

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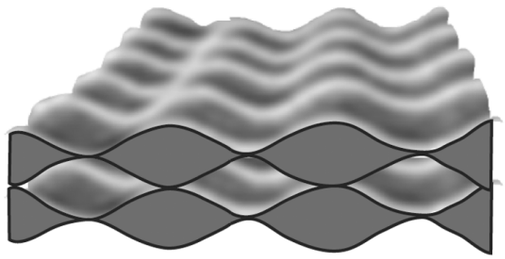

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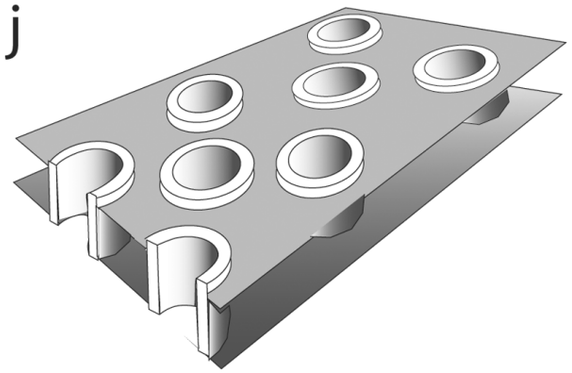

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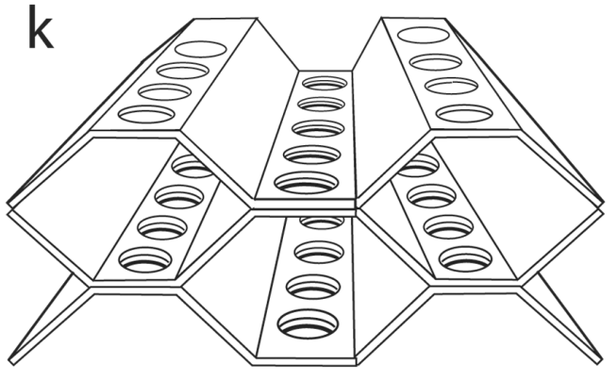

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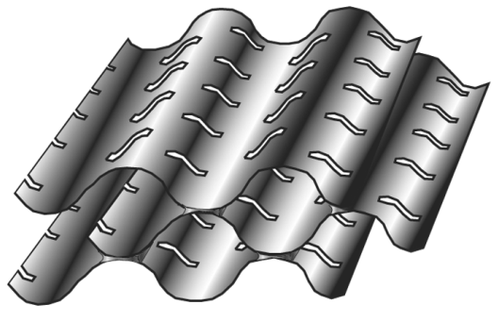

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